$T = 13$ double isobaric analog state in ^{138}Ce via pion-induced double charge exchange

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Pion double charge exchange on ^{138}Na ($T=13$), at a bombarding energy of 292 MeV, and a scattering angle of 5°, has been used to populate the double isobaric analog state in ^{138}Ce. The measurements provide determinations of Q value, width, and center-of-mass cross section. Results are compared with systematics and with the isobaric-multiplet-mass equation.

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This experiment was performed to measure the energy, width, and cross section for populating the double isobaric analog state (DIAS) on a target of ^{138}Ba. Virtually nothing is known about the DIAS in nuclei in this mass region.

Extensive studies of the isobaric analog state (IAS) have been made for both light and heavy nuclei [1–4]. The DIAS has also been observed in many light nuclei [5], but its high excitation in heavy nuclei makes it more difficult to study [6]. Pion-induced double charge exchange (DCX) above the $\Delta_{3,3}$ resonance is able to select the DIAS from the large number of lower isospin states forming a background in the continuum. The selectivity has been demonstrated by the observation of the DIAS of ^{209}Bi [7] and ^{208}Pb [8]. Figure 1 presents all the published DIAS cross sections at 292 Mev [9,10]. The dearth of measurements for $A=90$–208 is apparent. We report here the population of the $T=13$ DIAS in ^{138}Ce using the ^{138}Ba $(\pi^-,\pi^-)^{138}$Ce reaction at $T_\pi=292$ MeV. This is the first observation of the DIAS in the $A=90$–208 region.

Pion-induced double charge exchange allows important tests to be made for a number of models of nuclear structure. A recent study of the isobaric-multiplet-mass equation (IMME) parameters for multiplets with large isospin [11] was based on data extracted from pairs of analog states, with each pair having different isospin. By using double charge exchange, it becomes possible to study a third member of an isospin multiplet, and hence to extract IMME parameters for a triplet of states in the same isospin multiplet.

The width of the DIAS has been predicted to be twice that of the isobaric analog state [12,13]. Because the width of the IAS increases with A, this hypothesis is easier to test for heavy nuclei. Only one width measurement of a DIAS has been reported previously [8]. Our ability to acquire high-resolution data on a target very much lighter than Pb provides a test of this prediction.

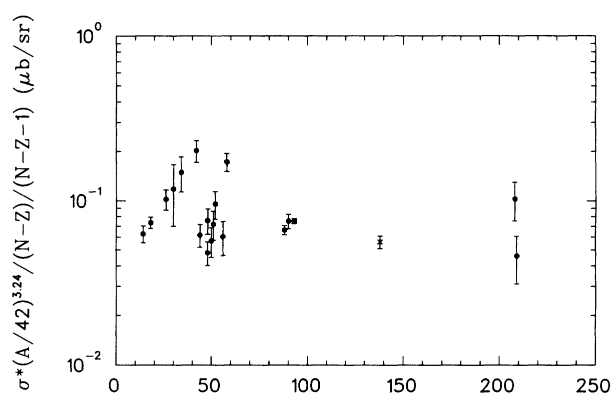

FIG. 1. Plot of published DIAS cross sections against A (dots). The quantity plotted is $\sigma(A/42)^{3.24}/(N-Z)(N-Z-1)$, where σ is the DIAS differential cross section at 292 MeV and 5°. The ^{138}Ba result (cross) is from the present work.

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The data was obtained using the EPICS facility (modified for DCX studies [14]) at the Clinton P. Anderson Meson Physics Facility (LAMPF). The target was ^{138}Ba, 327 mg/cm^2 in areal density and isotopically enriched to greater than 99%. A complete set of measurements consists of four points: elastic scattering on the ^{138}Ba target, DCX on Ba, elastic scattering on a reference target (chosen here to be ^{12}C), and DCX on the reference target. The use of Ba elastic scattering allows a determination of the effective beam energy—with effects of the channel momentum calibration and energy loss in the target combined. Because energy loss can be relatively easily computed, reliance on the spectrometer calibration allows the absolute channel energy to be determined. As pointed out later, however, these two effects can be made to cancel in determining the DCX Q value. The Ba elastic scattering also allows for a measurement of the experimental line shape for a state that is known to have no natural width. Excited states of ^{138}Ba present no difficulty. The energy resolution was measured as 440 keV FWHM, using elastic scattering at 35° (with the target rotated to give the same thickness as for the 5° DCX measurements). A Gaussian peak with an exponential tail gives a good account of the elastic data. Contributions due to detector-system resolution and straggling in the target are estimated to be 150 and 90 keV, respectively. The remaining (dominant) contribution was attributed to the beam resolution, caused by wandering magnetic fields.

The combination of elastic scattering and DCX on a reference target whose DCX Q value is known allows a check on the spectrometer calibration. (Because the DCX Q values of interest are considerably negative, the spectrometer magnetic field is changed between the elastic and the DCX measurements to put the relevant peaks in approximately the same location on the focal plane.) The C and Ba elastics were measured with one spectrometer setting, the C and Ba DCX with one other setting. The channel fields were kept constant throughout (except for the field drifts referred to above).

During the DCX measurements, the runs were terminated after approximately four hours to check and readjust (if necessary) the magnetic fields. The DCX data presented here consists of approximately 57 h for ^{138}Ba and 15 h for ^{12}C. Pions were distinguished from electron backgrounds using a threshold Cherenkov detector, and from muon backgrounds using a large absorber which exploits the different ranges of pions and muons in graphite. Absolute normalization was determined by measuring hydrogen elastic scattering (with a CH_2 target), and comparing the measured yield with the known π-nucleon cross section [15].

The complete set of four missing-mass histograms are displayed in Fig. 2. A variety of fits were performed for the Ba DCX spectrum, using the code NEWFIT after correcting for the measured spectrometer acceptance. Both exponential and polynominal (up to third-order) backgrounds were tried. Using either a Gaussian or a Lorentzian peak shape for the DIAS, without folding in the elastic line shape, demonstrates that the DIAS width is larger than the experimental resolution. The two best-fit peak shapes are compared in Fig. 3. For accurate determinations of the DIAS Q value and width we have used a Lorentzian folded with the experimental (elastic) line shape. A few (three or four) additional states are observed below the DIAS, and the giant dipole resonance (GDR⊗IAS) is above the DIAS. Adding these peaks to the fit (Fig. 4) has little effect on the DIAS Q value and width, but their presence in the fit does slightly increase the extracted DIAS cross section because of the resulting lowering of the fitted background.

The various DIAS fits are summarized in Table I. The DIAS Q value listed here is actually the difference between missing mass for Ba elastics and for the DIAS.

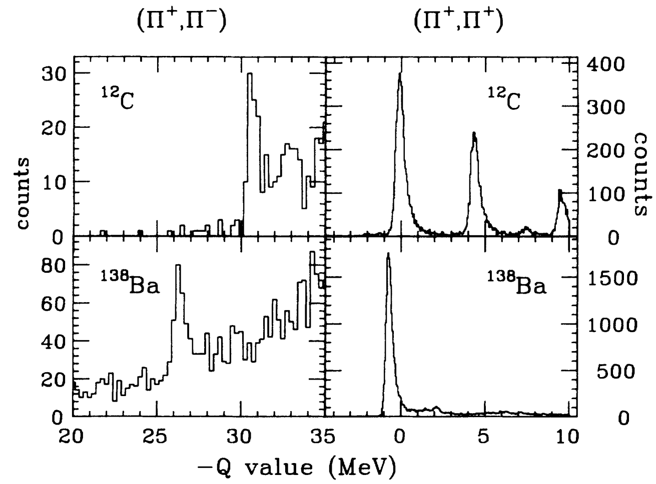

FIG. 2. Raw data for the barium DCX (showing the DIAS). The ^{12}C DCX (^{12}O ground state) and elastic data (at 35°) for both targets are also shown. The data have not been corrected for an offset of 1.5 MeV in beam energy, or for energy losses in the target (0.42 MeV for ^{138}Ba and 1.02 MeV for ^{12}C).

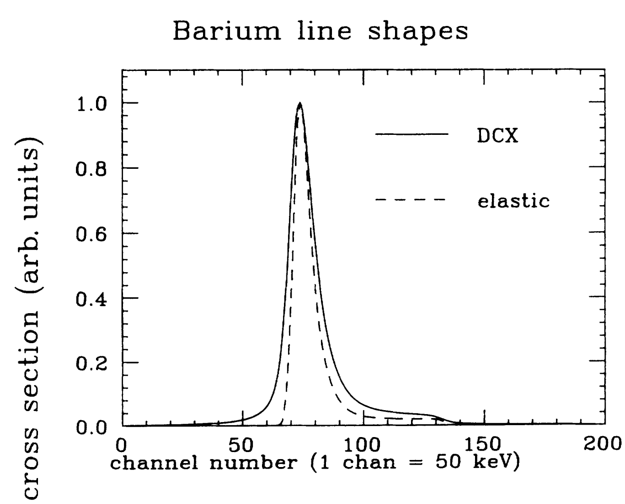

FIG. 3. Line shapes for the barium elastic (dashed) and DIAS (solid) peaks. The energy scale offsets and the yields have been arbitrarily normalized.

TABLE I. Summary of ^{138}Ba DIAS fits.

Peak shape	Background type	$-Q$ (MeV)	Width (MeV)	$d\sigma/d\Omega$ (μb/sr)
Lorentzian only	Cubic poly.	27.230±0.026	599±30	0.73±0.07
Lorentzian folded with elastic	Cubic poly.	27.100±0.040	194^{+100}_{-80}	0.59±0.06
Lorentzian only	Exponential	27.230±0.040	570±54	0.69±0.07
Lorentzian folded with elastic	Exponential	27.100±0.030	185^{+80}_{-90}	0.63±0.06
Best values		27.100±0.035[a]	189^{+90}_{-85}	0.61±0.06[b]

[a]Measured quantity. After applying corrections discussed in the text, this becomes 27.240±0.070.
[b]When other peaks are added to the histogram (see Table II and Fig. 4) the DIAS cross section is increased to 0.77±0.07 μb/sr.

Thus the effects of channel miscalibration and energy loss in the target have canceled out (except for a slight difference in energy loss for 292- and 260-MeV pions of about 10 keV).

Correcting the elastic peak energy for target energy loss gives beam kinetic energies of 293.13 and 293.17 MeV for ^{12}C and ^{138}Ba targets, respectively, rather than the nominal value of 292 MeV. This is a known effect—caused by saturation of the EPICS channel dipole magnets at high fields. A difference of 44.7 keV between these two numbers comes from the kinematic shift of the carbon elastic due to an angle offset of 0.3°.

The best DIAS Q value is -27.100 ± 0.035 MeV, the width is 189^{+90}_{-85} keV, and the center-of-mass cross section is 0.61±0.06 μb/sr [0.77±0.07 μb/sr with the other peaks in the spectrum (see Fig. 4 and Table II)].

The DIAS Q value quoted above still has to be corrected for the spectrometer calibration. This information is obtained from the combination of ^{12}C elastic and DCX data. The known ^{12}C DCX ground-state Q value is -31.034 ± 0.048 MeV [16]. Our measured difference between elastic and DCX ground-state missing mass is -30.859 ± 0.060 MeV. The difference between this value and the known one presumably arises from the use of a slightly increased magnet constant in the spectrometer calibration. If we assume this correction is linear, we should make our Ba DCX Q value [192 keV $(=31.034-30.859)27.11/31.034$ MeV] more negative. Thus, the final Q value we quote is -27.240 ± 0.070 MeV, where most of the uncertainty is from correcting the magnet calibration. Using the ground-state DCX Q value of 0.324 MeV [17] and our Q value yields an excitation energy of 27.66 MeV for the DIAS in ^{138}Ce. The ^{12}C(π^+,π^-)^{12}O ground-state cross section was 57±7 nb/sr.

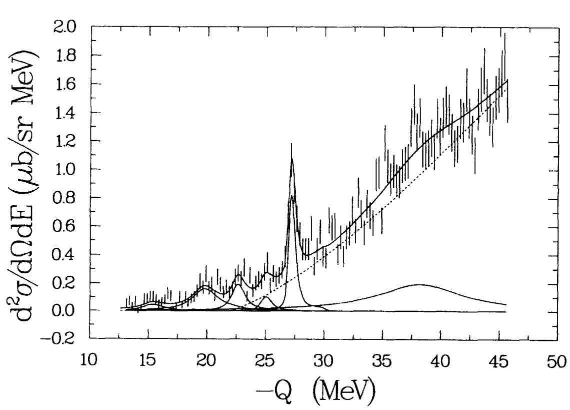

FIG. 4. Missing-mass histogram for DCX on ^{138}Ba, at 292 MeV and 5°, fitted with the DIAS, the GDR⊗IAS, and four peaks below the DIAS. Results are in Table II.

In a simple model, the Q value to the DIAS is given by

$$-Q_{\mathrm{DIAS}}=\Delta E_{C,1}+\Delta E_{C,2}-2\Delta_{np} , \quad (1)$$

where Δ_{np} is the neutron-proton mass difference and $\Delta E_{C,1}$ and $\Delta E_{C,2}$ are the Coulomb displacement energies for the isobaric analog state and the DIAS. For $\Delta E_{C,1}$ we use 14.728 MeV, the average Coulomb displacement energy for ^{137}La [18]. For $\Delta E_{C,2}$ we use 14.859 MeV, obtained from the value for ^{139}Ce [18] (14.800 MeV) increased by 59 keV to allow for the change in mass to ^{138}Ce. Using $\Delta_{np}=1.293$ MeV gives $Q_{\mathrm{DIAS}}=-27.001$ MeV. As the Coulomb displacement energies are estimates, we consider this result to be in reasonable agreement with our observed Q value. The deviation of 0.24 MeV would have been 0.10 MeV if we had used the absolute magnet calibration, rather than correcting for the

TABLE II. Complete results from DCX on ^{138}Ba. Final fit χ^2 is 1.13.

$-Q$ (MeV)	Width (MeV)	$d\sigma/d\Omega$ (μb/sr)
15.26±0.10	1.90±0.10	0.146±0.042
19.68±0.10	2.36±0.20	0.642±0.068
22.55±0.10	1.00±0.10	0.391±0.056
24.97±0.10	0.69±0.10	0.168±0.052
27.180±0.035	0.25±0.10	0.770±0.069
37.99±0.50	8.8±1.0	2.64±0.32

^{12}C Q value.

The width of the DIAS has been predicted [12] to be twice that of the IAS. The width of the DIAS was determined as the width of the Lorentzian, which was convoluted with the elastic line shape to fit the DIAS. Figure 3 shows the two line shapes. Estimating the average width of the IAS in ^{137}La [2] to be the same as that in ^{138}La, we expect a DIAS width of 128±60 keV. Although this is consistent with our fitted width of 189^{+90}_{-85} keV, the uncertainties are too large to provide a rigorous test of this model.

The DIAS cross section can be estimated from fits to the A-dependence systematics [19,20]. Expressions of the form

$$\frac{d\sigma}{d\Omega}(5^\circ)=\sigma_0(N-Z)(N-Z-1)\left[\frac{A}{42}\right]^{\alpha} \quad (2)$$

have previously been used to fit the 5° cross sections. In a simple diffractive model [21] $\alpha=-\frac{10}{3}$. In the fit of Ref. [19], $\sigma_0=0.068$ μb/sr and the best-fit $\alpha=-3.24\pm0.05$, giving an expected cross section of 0.936 μb/sr for the DIAS on ^{138}Ba, which is considerably larger than the measured cross section of 0.77±0.07 μb/sr. In a more recent fit [20], α was constrained to be $-\frac{10}{3}$, and the fitted σ_0 gives a cross section prediction of 0.843 μb/sr, which is in somewhat better agreement with our measurement.

The isobaric-multiplet-mass equation [22] relates the masses of the parent state, the IAS, and the DIAS,

$$M(T_Z)=a+bT_Z+cT_Z^2 , \quad (3)$$

where $M(T_Z)$ are the masses of the members of an isospin multiplet. The A dependence $(61\le A\le 125)$ of b has been fitted by [11]

$$b=\Delta_{nH}-\left[\frac{1.411}{2}\right]A^{2/3}+0.819 \text{ MeV} , \quad (4)$$

which gives an estimate of $b=-17.239$ MeV for $A=138(\Delta_{nH}=\Delta_{np}-m_e)$. Similarly, c can be estimated by

$$c=\frac{-b+\Delta_{nH}}{A-1} , \quad (5)$$

giving $c=0.132$ MeV. The atomic mass differences between the IAS and the parent state (Δ_1) and the DIAS and the parent state (Δ_2) are

$$\Delta_1=M(T)-M(T-1)=b+c(2T-1) , \quad (6)$$

$$\Delta_2=M(T)-M(T-2)=2b+c(4T-4) . \quad (7)$$

Using our measured DIAS Q value, and estimating $M(T-1)$ from the IAS Coulomb displacement energy, gives

$$\Delta_1=-\Delta E_{C,1}+\Delta_{nH}=-13.943 \text{ MeV} , \quad (8)$$

$$\Delta_2=Q_{\text{DIAS}}-2m_e=-28.260\pm0.07 \text{ MeV} . \quad (9)$$

Solving Eqs. (6) and (7) for b and c gives $b=-18.6\pm0.9$ MeV and $c=0.188\pm0.035$ MeV. The results are not in agreement with the above estimates (which do not include second-order corrections [23,24]). The uncertainties for b and c do not include an estimate for the uncertainty of $\Delta E_{C,1}$.

In conclusion, we have used pion-induced double charge exchange to study the DIAS of the ^{138}Ba ground state. A Q value of -27.24 ± 0.07 MeV was obtained, and a 5° cross section of 0.77±0.08 μb/sr was measured. The cross section is slightly lower than expected from the known A dependence of transitions to the DIAS in DCX. The Q value is slightly more negative than an estimate using the Coulomb displacement energies of charge-exchange transitions between members of the isospin multiplet. In addition, simple estimates of the IMME parameters for $A=138$, $T=13$ are not consistent with those determined from the measured DIAS Q value and the estimated IAS Coulomb displacement energy. It would be interesting to see if similar deviations are present in other rare-earth nuclei. The width of the DIAS (190±90 keV) is consistent with a prediction using a model of Coulomb mixing with states of lower isospin.

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